PERFORMANCE GRADED BITUMEN SPECIFICATIONS

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ABSTRACT

Penetration graded specifications for bituminous binders focus on the low service temperature (25°C) properties of the binder. However, in much of the Asian region the main failure mechanism is related to deformation at high service temperature. Because allowance must be made in specifications for a range of binder temperature susceptibilities, penetration graded binders have a wider range of deformation resistance at high service temperatures (60°C) than viscosity graded binders. This means that penetration graded bitumens can be more prone to rutting than viscosity graded bitumens.

The penetration test is empirical; it does not involve the measurement of any fundamental engineering parameters. Recognising the limitations of empirical testing, the US Strategic Highway Research Program (SHRP) sponsored a major research effort to develop performance based tests and specifications for binders and hot mix asphalt mixes. This resulted in the development of the Superpave Performance Grading (PG) system which has had significant impact on binder specifications outside the US.

However, it can be shown that the PG grade, when applied to bitumens, is in fact a surrogate for viscosity. In the case of polymer modified binders, the relationship between PG grade and field performance is open to doubt and additional specification requirements are often used in the US. A viscosity graded specification would have advantages over a penetration based specification in the Asian region where high temperatures are experienced. It would also be cheaper and simpler to implement than the PG system.

1. INTRODUCTION

Most Asian bitumens are specified by the Penetration Test at 25°C. The bitumen samples are subjected under a 100 g load for a duration of 5 s at 25°C. Designation used is according to the penetration range i.e. 40/60 pen bitumen has a penetration range between 40 and 60 deci millimetres (dmm). Table 1 shows the properties of two typical Asian penetration graded bitumens. [1]

Before the introduction of the Superpave Performance Grading (PG) specification, The US had adopted the penetration grading system. In 1918, the Bureau of Public Roads (now the Federal Highway Administration, FHWA) introduced the penetration grading system by developing various penetration grades suited to different climatic conditions and applications. Penetration grading was developed to characterise the consistency of bitumen. The specification covered the following bitumen characteristics: [2]

- bitumen penetration at 25°C
- flash point temperature
- ductility at 25°C
- solubility in trichloroethylene
- thin film oven test.

Further information can be obtained from AASHTO M 20-70 (2004) and ASTM D946-82 (2005). [3], [4]

Table 1: Properties of two typical Asian bitumens

Properties	80/100		60/70	
	Min	**Max**	**Min**	**Max**
Penetration at 25°C, 0.1mm	80	100	60	70
Softening point, °C	45.0	52.0	45.0	52.0
Flash point, °C	276	-	276	-
Ductility at 25°C, cm	100	-	100	-
Loss on heating (LOH), %wt	-	0.75	-	0.75
Penetration of residue, after LOH, % of original	70	-	70	-
Wax content, %wt	-	-	-	2.0

2. AUSTRALIAN VISCOSITY GRADING

In 1977, Australia moved from a penetration graded specification to one that is based on viscosity at 60°C. The classification based on viscosity at 60°C centres on the service temperature which is critical to the conditions in Australia.

The current Australian standard (AS2008-1997) controls the flow properties of bitumen at high and intermediate service temperatures by means of viscosity and penetration requirements. These requirements control an important bitumen characteristic, namely temperature susceptibility (change in properties with temperature).

To confine bitumen to an acceptable range of temperature susceptibilities, limits were imposed on the viscosity tests at 60°C and 135°C. To exclude bitumens of high temperature susceptibility, which might be too brittle at low road temperatures, a minimum limit was placed on the penetration value at 25°C. An extract of the current standard is shown in Table 2. [5]

Table 2: Properties of residual bitumen for pavements for Class 170 and 320 bitumens in AS2008 -1997

Property	Class 170		Class 320	
	Min	**Max**	**Min**	**Max**
Viscosity at 60°C, Pa.s	140	200	260	380
Viscosity at 135°C, Pa.s	0.25	0.45	0.40	0.65
Penetration at 25°C (100 g, 5 s), *pu*	62	-	40	-
Flashpoint, °C	250	-	250	-
Short term effect of heat and air (RTFOT)	-	-	-	-
Viscosity of residue at 60°C as % of original	-	300	-	300

Note: Penetration unit, 1 *pu* = 0.1 mm

3. US VISCOSITY GRADING

A viscosity graded specification was developed in the early 1960s to replace the empirical penetration test as the key bitumen characterisation property, and to measure consistency at 60°C rather than 25°C. This specification quantifies the following bitumen characteristics:

- viscosity at 60°C
- viscosity at 135°C
- penetration (100 g load for 5 s at 25°C)
- flash point temperature
- ductility at 25°C
- rolling thin film oven test (RTFO).

The viscosity grading can be applied not only to originally supplied bitumen samples (referred to as AC: asphalt cement) but also aged residue samples (AR). The AR samples are RTFO treated bitumen samples used to simulate the properties of bitumen after it has undergone a typical asphalt mixing process. Further information can be obtained from AASHTO M 226-80 (2004) and ASTM D3381-92 (1999). [6], [7]

4. SUPERPAVE PERFORMANCE GRADING (PG SYSTEM)

Recognising the limitations of the empirical testing, the Strategic Highway Research Program (SHRP) sponsored a US$ 50 million research effort to develop performance based tests and specifications for binders and hot mix asphalt mixtures in 1987.

The main features of the Superpave tests and specifications are: [8]

- instead of performing a test at a constant temperature and varying the specified value, the temperature at which the specified criteria (kept constant) must be met varies in consideration of the binder grade selected for the prevalent climatic conditions
- physical properties measured are directly related to field performance by engineering principles
- the testing regime simulates the three critical stages of a binder’s life. Refer to Section 4.3 for further details
- the entire range of pavement temperatures experienced at the project site is considered
- the tests and specifications are designed to eliminate or control three specific types of pavement distresses i.e. rutting (high temperatures), fatigue cracking (intermediate temperatures) and thermal cracking (low temperatures)
- SI units are used for the specifications developed and not imperial units, as previously.

In the Superpave performance specification (M320-05), SHRP introduced two important properties to determine the performance grading of a binder over a range of temperatures and loading rates (angular frequency) i.e. complex modulus (G*) and phase angle (δ), see Table 3. These two properties can be measured using a Dynamic Shear Rheometer (DSR). [9]

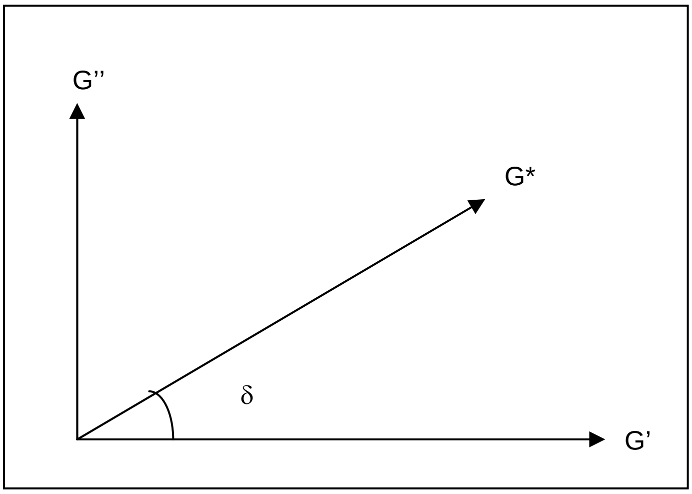
Table 3: Extract from the current Superpave performance grading system (M320-05)

<table>
<tr><td>Performance Grade</td><td colspan="5">PG 58</td><td colspan="6">PG 64</td><td colspan="6">PG 70</td><td colspan="5">PG 76</td><td colspan="5">PG 82</td></tr>
<tr><td>Average seven day maximum pavement design temperature, °C</td><td colspan="5">< 58</td><td colspan="6">< 64</td><td colspan="6">< 70</td><td colspan="5">< 76</td><td colspan="5">< 82</td></tr>
<tr><td>Minimum pavement design temperature, °C</td><td colspan="5">>(-16) >(-10) >(-16) >(-22) >(-28) >(-34) >(-40)</td><td colspan="22">>(-10) >(-16) >(-22) >(-28) >(-34) >(-40)</td></tr>
<tr><td colspan="28">Original binder</td></tr>
<tr><td>Dynamic shear (T315), G*/sinδ, min 1 kPa test temperature @ 10 rad/s, °C</td><td colspan="5">58</td><td colspan="6">64</td><td colspan="6">70</td><td colspan="5">76</td><td colspan="5">82</td></tr>
<tr><td colspan="28">RTFO treated binder (T240)</td></tr>
<tr><td>Dynamic shear (T315), G*/sinδ, min 2.2 kPa test temperature @ 10 rad/s, °C</td><td colspan="5">58</td><td colspan="6">64</td><td colspan="6">70</td><td colspan="5">76</td><td colspan="5">82</td></tr>
<tr><td colspan="28">Pressure ageing vessel residue (R 28)</td></tr>
<tr><td>PAV aging temperature, °C</td><td colspan="5">100</td><td colspan="6">100</td><td colspan="6">100 (110)</td><td colspan="5">100 (110)</td><td colspan="5">100 (110)</td></tr>
<tr><td>Dynamic shear (T315), G*/sinδ, min 5000 kPa test temperature @ 10 rad/s, °C</td><td>25</td><td>22</td><td>19</td><td>16</td><td>13</td><td>31</td><td>28</td><td>25</td><td>22</td><td>19</td><td>16</td><td>34</td><td>31</td><td>28</td><td>25</td><td>22</td><td>19</td><td>37</td><td>34</td><td>31</td><td>28</td><td>25</td><td>40</td><td>37</td><td>34</td><td>31</td><td>28</td></tr>
</table>

4.1 Interpretation of G* and δ

G* is defined as the ratio of stress developed and the strain imposed. By using sinusoidal loading in the DSR, the stress and strain developed varies periodically and the frequency of loading can be varied within a test. G* indicates the stress resulting from the strain. Phase angle (δ), which is expressed in degrees, is the phase shift between the applied stress and strain response of the material. This property ranges from 0° for a simple elastic material to 90° representing a simple (Newtonian) viscous material.

Combinations of G* and δ are used to characterise the visco-elastic properties of a binder.



G* is made up of two components i.e. viscous component (G'') and elastic component (G')

To derive (G') and (G'') from G* and δ:

Elastic component, (storage modulus)	G'	=	G* cos δ
Viscous component, (loss modulus)	G''	=	G* sin δ

Figure 1: Relationship between G* and the components G' & G''

4.2 SHRP Properties

The PG grading system covers both the high and low service temperatures likely to be experienced by a binder, refer to Table 4.

For high service temperature, the PG system defines the specification starting from 46°C through to 82°C in 6°C intervals. To meet the specification requirement, the value of **G*/ sinδ** needs to be a minimum of 1 kPa at the grading temperature and not exceed the requirements of the next grade.

At low service temperature, PG defines the specification requirement as **G*sinδ**. This paper, however, will not discuss the low service temperature aspect of the PG system since much of the Australasian region does not experience such low temperature conditions.

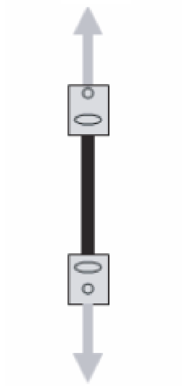
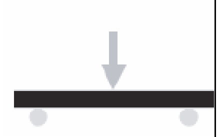
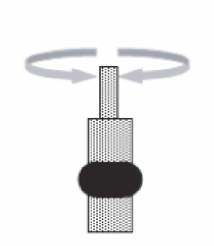
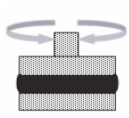
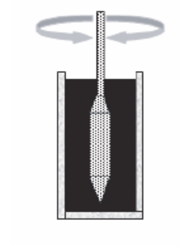
4.3 PG Tests and Specifications

The PG system measures the physical properties of binders through tests that are intended to be directly related to field performance by engineering principles. These tests are conducted under the temperature extremes a pavement experiences to simulate the three critical stage of a binder's life, namely: [10]

1. first stage – transportation, storage and handling prior to mixing with aggregate
2. second stage – after mixing production and construction (RTFO treatment is used to approximate this stage of short-term ageing)
3. third stage – binder ageing on the road (the pressure ageing vessel (PAV) is used to simulate long-term ageing of the binder).

Table 4 lists some of the test equipment, temperatures, performance related parameters and ageing conditions of a binder. [11]

Table 4: PG graded criteria, tests, temperatures and ageing conditions

Performance Criteria	Low temperature cracking		Fatigue cracking	Rutting	Construction/ workability
Test	Direct Tension Test (DTT) 	Bending Beam Rheometer (BBR) 	Dynamic Shear Rheometer (DSR) 	Dynamic Shear Rheometer (DSR) 	Rotational Viscometer (RV) 
Purpose	Measure binder properties at low service temperatures	Measure low temperature stiffness and failure properties	Measure binder stiffness and elasticity properties at high and intermediate temperatures (modulus, G*; phase angle, δ)		Measure binder viscosity at high temperatures
Temperature	Minimum pavement surface temperature		Intermediate pavement temperature	Average 7-day maximum pavement temperature	Mixing/ compaction temperature
Ageing Condition	Short-term ageing (RTFO) plus long-term ageing (PAV)			No ageing and also short-term ageing (RTFO)	No ageing

4.4 Performance Grade Nomenclature

Superpave performance grading is reported using two numbers. The first number indicates the average seven day maximum pavement temperature (°C) while the second shows the minimum pavement design temperature (°C). For example, a PG 64-28 is intended for use in an environment where the average seven day maximum pavement temperature is 64°C and the expected minimum pavement temperature is -28°C.

The working temperature range determines whether a given grade of bitumen requires special manufacture or addition of a modifier. For example, a PG 64-28 has a working range of 92° (64 + 28 = 92). Usually, binders with a temperature difference of 92° or more would generally require some sort of modification (Table 5).

Table 5: PG grades for different bitumen blends

Low temperature (°C)		High temperature (°C)				
		52	58	64	70	76
	-16	52-16	58-16	64-16	70-16	76-16
	-22	52-22	58-22	64-22	70-22	76-22
	-28	52-28	58-28	64-28	70-28	76-28
	-34	52-34	58-34	64-34	70-34	76-34
	-40	52-40	58-40	64-40	70-40	76-40

White	Crude oil
Light grey	High quality crude oil
Dark grey	Modifier required

7. DISCUSSION

7.1 Penetration vs Viscosity

The penetration test is an empirical one and does not measure a fundamental engineering parameter such as viscosity. It is also impossible to determine the temperature susceptibility of a bitumen based on a single test conducted at 25°C. By contrast, in the viscosity grading system, the bitumen is tested at three different temperatures i.e. viscosity at 60°C, 135°C, and penetration at 25°C.

The comparison between the properties of a viscosity graded bitumen and a penetration graded bitumen is illustrated in Figure 3a and 3b. [12] For discussion sake, an Australian Class 170 (refer to Table 2) and a Shell Singapore 60/70 bitumen (Shell specification indicates that this bitumen must achieve a minimum of 180 Pa.s at 60°C) were selected. At 60°C (regarded as the critical performance temperature in most tropical countries), the penetration graded bitumen has a much wider range of deformation resistance (Figure 3b) than the viscosity graded bitumen (Figure 3a). This means that penetration graded bitumens can be more prone to rutting than viscosity graded bitumens.

A sample of the penetration graded 60/70 bitumen used on the Hong Kong airport runway was collected and tested by the ARRB Group. There is a perception that a 60/70 penetration bitumen has a similar viscosity at 60°C to a Class 320 (refer Table 2) bitumen. However, this is not necessarily the case based on the discussion above. Ultimately, the asphalt for which it was used, was advised to be suffering closing and severe damage to the grooved surface. This bitumen was tested to have a viscosity of 253 Pa.s at 60°C – much softer than a Class 320. [13]

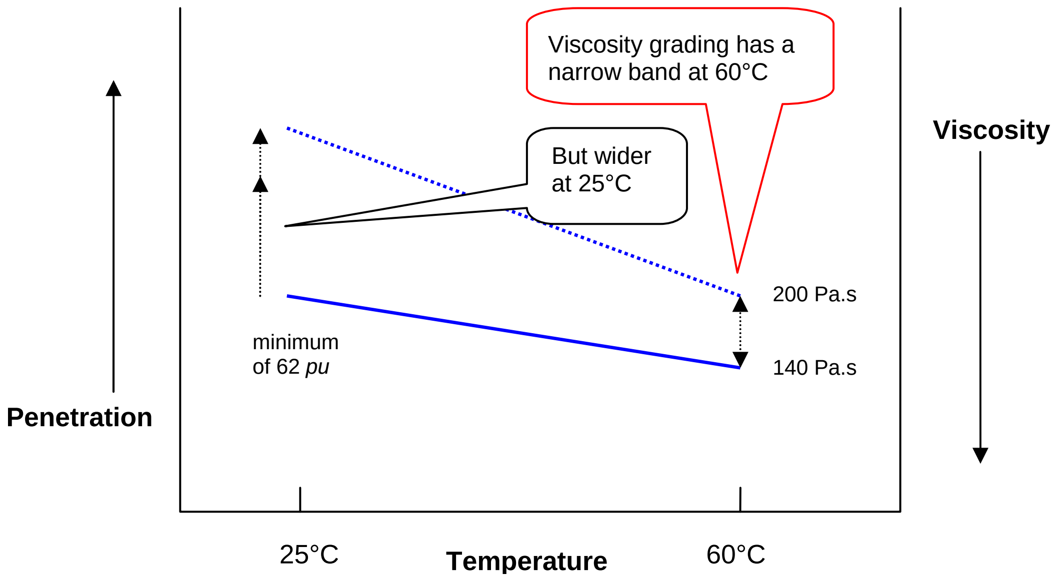


Figure 3a: Illustration of the penetration and viscosity properties of an Australian Class 170 bitumen

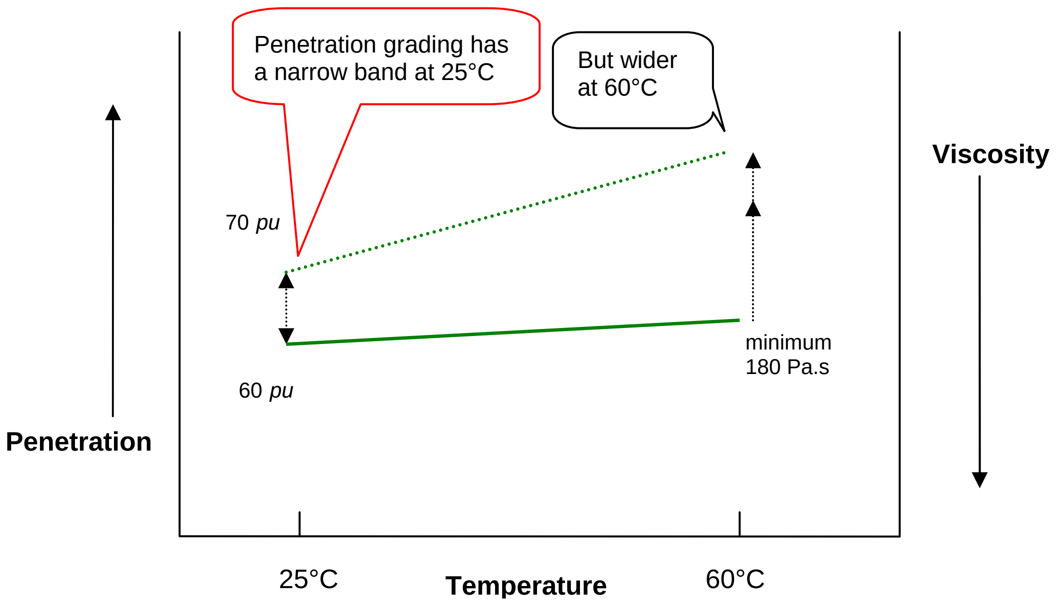


Figure 3b: Illustration of the penetration and viscosity properties of a Shell Singapore 60/70 bitumen

7.2 PG vs Viscosity

According to the Superpave testing protocol, G* is determined at a defined shear strain rate (10 rad/s). Since most bitumens have a phase angle greater than 80°, whereby sin δ approximates to 1, the term G* sin(δ), used to define the Superpave grade is actually a surrogate for viscosity. The following equations explain the reasoning. [8]

Viscosity, $\eta = G''/\omega$

where,

G'' = viscous component

ω = loading rate

Therefore, $\eta = G^*\sin(\delta)/\omega$ Relationship of G* and G'' shown in Figure 1 when,

$\omega =$ 10 rad/s (refer Table 4)

$\delta >$ 80°

$\sin\delta \approx$ 1

$$\eta \approx \mathbf{G^*/10}$$

Under these circumstances ($\sin\delta \approx 1$), complex modulus G* is exactly one tenth the numerical value of viscosity. Hence, the Superpave temperature value is an equi-viscous temperature.

The Superpave high pavement temperature (refer to Section 4.4) is plotted against viscosity at 60°C for untreated and RTFO treated bitumens in Figure 4. If the Superpave temperature is plotted against the logarithm of viscosity, a straight line is obtained. However, it was decided to keep the viscosity to units that practitioners are more familiar with i.e. Pa.s. Allowing experimental errors, there appears to be a strong correlation between the high temperature used in the SHRP PG system and viscosity at 60°C used in the Australian grading system. [13]

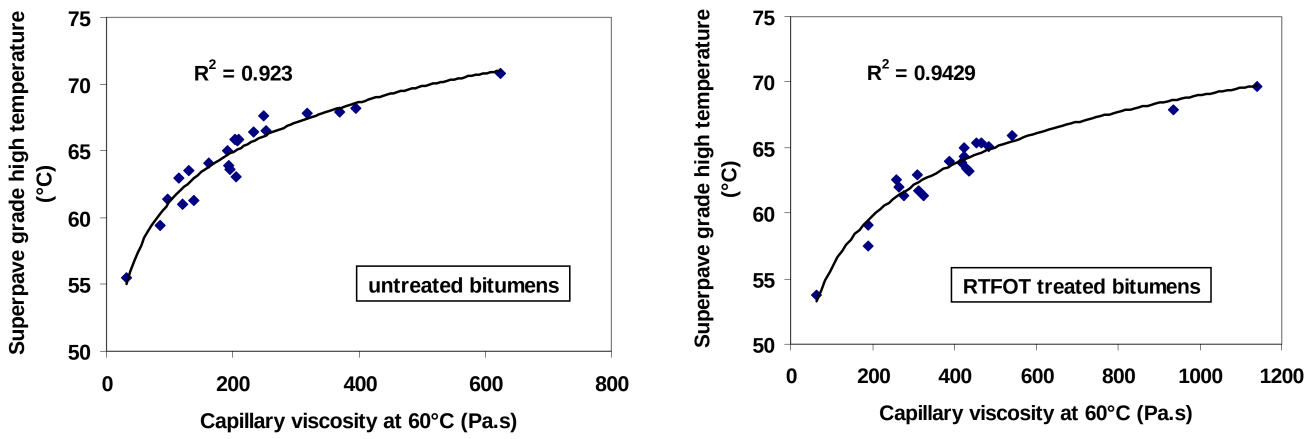


Figure 4: Superpave high temperature indicator against viscosity

8. CONCLUSIONS

Penetration based specification has its focus primarily on the low service temperature at 25°C. Whereas, viscosity graded specification controls the temperature susceptibility of a bitumen by means of viscosity at the critical performance temperature of 60°C.

The Australian viscosity graded binders have a banded specification at 60°C and only specifies a minimum value for the low temperature at 25°C. As a result of the narrower band at high service temperature, 60°C, the viscosity graded binders were shown to be more resistant to deformation when compared to penetration graded binders.

The US moved away from empirical testing towards a performance based specification. Under the PG system, two very important properties were introduced, namely complex modulus (G*) and phase angle (δ). These two properties are used to determine the PG of a binder.

From a global perspective, many Asian countries are seen to be moving towards adopting a performance based system as their primary bitumen classification. However, the Superpave PG system has been shown to have a strong correlation with the Australian viscosity grading. Superpave PG is essentially a surrogate of viscosity. For this reason, the viscosity testing at high service temperature should be highly considered as the performance based test many are looking for in their binders' specifications.

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